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Michael A. Shimokaji, Reg. No. 32,303

SINTERED SILICON NITRIDE

BACKGROUND OF THE INVENTION

5 [0001] The present invention generally relates to a sintered silicon nitride product. The present invention also relates to methods for making a sintered silicon nitride product.

[0002] Sintered silicon nitride compositions represent a group of ceramics useful as engineering components for high temperature applications, such as in
10 gas turbine engines. Some prior art sintered silicon nitride products have adequate mechanical properties and oxidation resistance at temperatures in the range of 900°C to 1400°C. However, such prior art products may exhibit major deficiencies in advanced gas turbine applications in which the turbine inlet temperature may exceed 1500°C.

15 [0003] U.S. Patent No. 4,401,768 to Morgan discloses a sintered silicon nitride prepared from a mixture of silicon nitride, silicon dioxide (silica), and scandium oxide (scandia). The sintered silicon nitride was produced by hot pressing at 1800°C to provide a product consisting of silicon nitride, silicon oxynitride, and scandium disilicate. Morgan does not disclose properties such
20 as fracture toughness or oxidation resistance at a temperature of 1500°C.

[0004] U.S. Patent No. 5,804,523 to Oda *et al.* discloses the production of sintered silicon nitride from a mixture of silicon nitride, silica, and an oxide of a Group 3a (Re) element, the Group 3a element at least including lutetium (Lu). The composition of the sintered product may contain intergranular crystalline
25 phases of a $\text{Re}_2\text{Si}_2\text{O}_7$ (disilicate) or a Re_2SiO_5 (monosilicate). Oda *et al.* discloses fracture toughness only in the range of about 4.5 to 6.5 MPa.m^{0.5}.

[0005] As can be seen, there is a need for a strong and reliable silicon nitride ceramic with improved mechanical stability and a high level of toughness at high temperatures. There is a further need for a sintered silicon nitride product which exhibits resistance to corrosion and oxidation at high
5 temperatures. The present invention provides such materials, and processes of making the same, as will be described in enabling detail hereinbelow.

SUMMARY OF THE INVENTION

10 [0006] In one aspect of the present invention, there is provided a sintered silicon nitride product comprising from about 60 to 95 mole % β -silicon nitride, and from about 1 to 8 mole % scandium oxide.

[0007] In another aspect of the present invention, a sintered silicon nitride product comprises not less than 50 mole % β -silicon nitride, about 0.1 to 30
15 mole % silicon carbide, about 1 to 15 mole % scandium disilicate, and about 1 to 10 mole % scandium oxide.

[0008] In a further aspect of the present invention, there is provided a sintered silicon nitride product comprising β -silicon nitride grains, silicon carbide, a grain boundary secondary phase of scandium oxide, and a grain
20 boundary secondary phase of scandium disilicate. The β -silicon nitride grains comprise about 72 to 92 mole %, the silicon carbide comprises about 3 to 18 mole %, the scandium oxide comprises about 3 to 6 mole %, and the scandium disilicate comprises about 1 to 4 mole %.

[0009] In still another aspect of the present invention, a sintered silicon
25 nitride product is formed by sintering a starting powder mix, the starting powder mix comprising about 80 to 95 weight % silicon nitride, about 0.25 to 10 weight % silicon carbide, and about 5 to 12 weight % scandium oxide.

[0010] In yet another aspect of the present invention, a component formed from a sintered silicon nitride comprises about 60 to 95 mole % β -silicon

nitride, about 2.5 to 25 mole % silicon carbide, about 1 to 10 mole % scandium disilicate, and about 1 to 8 mole % scandium oxide.

[0011] In another aspect of the present invention, a method for preparing a sintered silicon nitride product comprises providing a starting powder mix, forming a green body from the starting powder mix, and sintering the green body to form the sintered silicon nitride product; wherein the sintered silicon nitride product comprises about 60 to 95 mole % silicon nitride, about 2.5 to 25 mole % silicon carbide, about 1 to 10 mole % scandium disilicate, and about 1 to 8 mole % scandium oxide.

10 [0012] In an additional aspect of the present invention, a method for preparing a sintered silicon nitride product comprises providing a starting powder mix, forming a green body from the starting powder mix, and sintering the green body to form the sintered silicon nitride product. The starting powder mix comprises silicon nitride in the range of from about 80 to 95 weight %, silicon carbide in the range of from about 0.25 to 10 weight %, and scandium oxide in the range of from about 5 to 12 weight %. Sintering of the green body may include a plurality of gas pressure sintering stages, and the sintered silicon nitride product may comprise about 60 to 95 mole % silicon nitride, about 2.5 to 25 mole % silicon carbide, about 1 to 10 mole % scandium disilicate, and about 1 to 8 mole % scandium oxide. The sintered silicon nitride product prepared according to such a method has a fracture toughness in the range of from about 7.7 to 8.5 MPa.m^{0.5}.

[0013] These and other features, aspects and advantages of the present invention will become better understood with reference to the following drawings, description and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Figure 1 schematically represents a series of steps involved in a method for preparing a sintered silicon nitride product, according to one

embodiment of the invention; and

[0015] Figure 2 shows an X-ray diffraction pattern of a sintered silicon nitride product prepared according to the invention.

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DETAILED DESCRIPTION OF THE INVENTION

[0016] The following detailed description is of the best currently contemplated modes of carrying out the invention. The description is not to be taken in a limiting sense, but is made merely for the purpose of illustrating the
10 general principles of the invention, since the scope of the invention is best defined by the appended claims.

[0017] The present invention provides compositions and methods of making sintered silicon nitride products, which exhibit a combination of desirable properties, including high levels of resistance to oxidation and
15 recession, high strength, and high fracture toughness at high temperatures. As an example, sintered silicon nitride products of the invention are suitable for manufacturing hot section components of gas turbine engines, such as blades, nozzles, and combustion liners, which can experience turbine inlet temperatures up to 1500°C. This invention can also be applied to various other
20 aerospace, automotive, and chemical industry applications where ultra high temperature, anti-corrosion, and load bearing capabilities are required for structural components. Sintered silicon nitride products of the present invention differ from prior art products in having a composition which comprises from about 0.1 to 30 mole % silicon carbide, from about 1 to 10 mole % scandium
25 oxide, and from about 1 to 15 mole % scandium disilicate; and a fracture toughness in the range of from about 7.7 to 8.5 MPa.m^{0.5}.

[0018] According to one embodiment of the invention, a sintered silicon nitride product may be formed from a starting powder mixture or mix comprising appreciable amounts of silicon carbide (SiC) and scandium oxide (Sc₂O₃) in

admixture with silicon nitride (Si_3N_4) and silicon dioxide (SiO_2). A sintered silicon nitride product of the invention may comprise substantial quantities of silicon carbide (SiC), scandium oxide, and scandium disilicate ($\text{Sc}_2\text{Si}_2\text{O}_7$), together with silicon nitride.

5 **[0019]** As an example, a sintered silicon nitride product of the invention may be formed by gas-pressure sintering a starting powder mix comprising up to about 15 weight % of silicon carbide, wherein the starting powder mix further comprises silicon nitride, scandium oxide (scandia), and silicon dioxide (silica). Typically, silicon carbide is present in the starting powder mix in the range of
10 from about 0.25 to 10 weight %, usually in the range of from about 0.5 to 8 weight %, and often in the range of from about 2 to 6 weight %. In one embodiment, the starting powder mix comprises from about 8 to 10 weight % of silicon carbide.

15 **[0020]** Typically, silicon nitride is present in the starting powder mix in an amount of at least about 50 weight %, usually in the range of from about 80 to 95 weight %, and often in the range of from about 85 to 92 weight %. The starting powder mix for forming sintered silicon nitride products of the invention may include *added* silicon dioxide powder in an amount of from about 0 (zero) to 5 weight %, usually in the range of from about 0 (zero) to 3 weight %, and
20 often in the range of from about 1 to 3 weight %. Herein, note that where 0 (zero) weight % of silicon dioxide is stipulated for the starting powder mix, this denotes that silicon dioxide itself is not added to the starting powder mix, it being understood that at least trace quantities of silicon dioxide are anticipated to be present (as a contaminant) in the silicon nitride component of the starting
25 powder mix.

30 **[0021]** The starting powder mix for forming sintered silicon nitride products of the invention typically comprises scandium oxide in an amount of from about 5 to 12 weight %, usually in the range of from about 6 to 10 weight %, and often in the range of from about 6 to 8 weight %. The relative amounts of scandium oxide and silica in the starting mix may be selected to provide a

silicon dioxide:scandium oxide (silica/scandia) molar ratio < 2 . The silicon dioxide:scandium oxide ($\text{SiO}_2/\text{Sc}_2\text{O}_3$) molar ratio in the starting mix may be in the range of from about 0.3 to 1.99, typically from about 0.4 to 1.5, and often from about 0.4 to 1. These molar ratios include silicon dioxide present in the silicon nitride component of the starting material in an estimated amount equivalent to 1.2 weight % of oxygen as silicon dioxide in the silicon nitride component. For example, based on the 1.2 weight % oxygen (as silicon dioxide) in the silicon nitride component of the starting material, a starting powder mix comprising 8 weight % scandium oxide and about 90 weight % silicon nitride, and having no added silicon dioxide powder component, will have a silica/scandia molar ratio of about 0.6.

[0022] In sintered silicon nitride products formed from starting mixtures having a $\text{SiO}_2/\text{Sc}_2\text{O}_3$ molar ratio equal to or less than 1 (e.g., samples 2 to 7, Table 1), the predominant grain boundary phase of Sc_2O_3 may account for more than 50% of the grain boundary phases (Fig. 2). This is contrast to silicon nitride products of the prior art that have $\text{Sc}_2\text{Si}_2\text{O}_7$, $\text{Si}_2\text{N}_2\text{O}$, or Sc_2SiO_5 as the primary grain boundary phase.

[0023] A sintered silicon nitride product of the invention may comprise β -silicon nitride grains together with particulate silicon carbide, and grain boundary secondary phases of scandium disilicate and scandium oxide. The sintered silicon nitride product may typically comprise at least 50 mole % β -silicon nitride, usually in the range of from about 60 to 95 mole % β -silicon nitride, and often in the range of from about 72 to 92 mole % β -silicon nitride. From about 0 (zero) % to trace quantities of α -silicon nitride may also be present in some embodiments.

[0024] Typically, silicon carbide can be present in the sintered silicon nitride product in an amount in the range of from about 0.1 to 30 mole %, usually in the range of from about 2.5 to 25 mole % silicon carbide, and often in the range of from about 3 to 18 mole % silicon carbide. The sintered silicon nitride product typically comprises at least about 1 to 10 mole % scandium

oxide, usually in the range of from about 1-8 mole % scandium oxide, and often in the range of from about 3 to 6 mole % scandium oxide. Typically, scandium disilicate may be present in the sintered silicon nitride product in an amount in the range of from about 1 to 15 mole %, usually in the range of from about 1 to 10 mole % scandium disilicate, and often in the range of from about 1 to 4 mole % scandium disilicate.

[0025] Figure 1 schematically represents a series of steps involved in a method for preparing a sintered silicon nitride product, according to one aspect of the invention, wherein step 100 may involve providing a starting powder mixture.

[0026] Typically, step 100 may involve combining silicon nitride, silicon carbide, and scandium oxide. Silicon nitride may be typically included in the starting mixture in an amount of at least about 50 weight %, usually in the range of from about 80 to 95 weight %, and often in the range of from about 85 to 92 weight %. Silicon carbide may be typically included in the starting mixture in an amount of up to about 15 weight %, frequently in the range of from about 0.25 to 10 weight %, usually in the range of from about 0.5 to 10 weight %, and often in the range of from about 5 to 10 weight %. Scandium oxide may be typically included in the starting mixture in an amount of from about 5 to 12 weight %, usually in the range of from about 6 to 10 weight %, and often in the range of from about 6 to 8 weight %. In some embodiments, in the range of from about 0 to 5 weight % silica (e.g., as silicon dioxide powder) may also be added to the starting mixture.

[0027] Step 102 may involve forming a green body from the starting powder mixture. The green body may be formed by various forming methods for ceramics. For example, the green body may be formed by isostatic dry pressing or by slip casting. For the preparation of green bodies by isostatic dry pressing, the starting powder mixture may be mixed in a suitable solvent, such as isopropanol, and milled with milling media. Such milling may be continued for a period ranging from a few hours to about 1 day (24 hours) or more, and

typically for a period of from about 4 to 24 hours.

[0028] Thereafter, the milled powder may be dried, and then sieved through screens (e.g., at 100 mesh). Such treatment can typically provide a flow-able starting powder mixture which will flow into a dry-press mold. A mold
5 of suitable size and configuration may then be filled with the flow-able powder. The filled mold may be sealed, and subjected to an isostatic pressure (e.g., at about 25,000 psi) to form a compacted green body.

[0029] For the preparation of slip cast green bodies, the starting powder mixture may be mixed with de-ionized water to about 41 to 44 vol. %, and the
10 pH adjusted to a pH of about 9.5 to 10. Thereafter, the mixture may be milled with silicon nitride mill media, for a period similar to that described hereinabove for isostatic dry pressing, to provide a milled mixture. The milled mixture may be poured into plaster molds until enough water is removed to make the material semi-rigid. The semi-rigid body may then be placed in a drying oven
15 until the remaining water is removed to form the green body.

[0030] Step 104 can involve sintering the green body to provide a sintered silicon nitride product. Typically, the green bodies can be sintered to more than 99% of the theoretical density at final temperatures in excess of 1900°C. The dried green bodies may be sintered using a carbon furnace in a
20 pressure vessel. Step 104 may typically involve a multi-stage sintering process. In some embodiments, a four-stage sintering process can be employed to achieve the desirable grain boundary phase compositions and microstructures which provide superior high fracture toughness (e.g., from about 7.7 to about 8.5 MPa.m^{0.5}, Table 3) and high temperature properties (e.g., oxidation
25 resistance at 1500°C, Table 3) to the sintered silicon nitride. The multi-stage sintering process may be performed for a combined period in the range of from about 5 to 15 hours, more typically from about 6 to 12 hours, and often from about 7 to 11 hours. Details of multi-stage sintering cycles are presented hereinbelow (Table 2).

30 [0031] The sintering process of step 104 may be conducted under

pressure of nitrogen gas or, in some stages, under a mixture of nitrogen and argon, and at elevated temperatures, to suppress the decomposition of silicon nitrides. Exemplary sintering conditions, including pressure and temperature ranges, are shown in Table 2. After the multi-stage sintering process or step, a
5 sintered silicon nitride product of the invention is formed. Such a sintered silicon nitride product may be formed as a component, e.g., a hot section component for a gas turbine engine.

[0032] Due to the microstructure and grain boundary phases in the final sintered body, sintered silicon nitride products of this invention exhibit high
10 fracture toughness and excellent high temperature properties to about 1500°C. Sintered silicon nitride products of the invention may be characterized, *inter alia*, by having: a substantial scandium oxide content, typically in the range of from about 1 to 10 mole %; and a fracture toughness typically in the range of from about 7.7 to 8.5 MPa.m^{0.5}. (In contrast, as referred to hereinabove, Oda *et al.*
15 (U.S. Patent No. 5,804,523) discloses fracture toughness only in the range of about 4.5 to 6.5 MPa.m^{0.5}.) Fracture toughness was measured using the indentation-strength method at 20-kg indentation load. Sintered silicon nitride products of the invention may be further characterized by having a sintered density typically in the range of from about 3.15 to 3.25 g/cm³, usually at least
20 about 3.17 g.cm⁻³; and a 20-kg indentation fracture strength typically in the range of from about 330 to 370 MPa, and usually about 350 MPa. Sintered silicon nitride products of the invention may be still further characterized by having a high oxidation resistance at temperatures up to at least about 1500°C (Table 3), and resistance to recession. While not being bound by theory,
25 Applicant believes that resistance to recession of products of the invention is due, at least in part, to the presence of a Sc₂O₃ grain boundary phase, which has no silica activity. The lack of silica activity exhibited by Sc₂O₃ improves the high temperature environmental resistance of sintered silicon nitride products of the invention, compared with prior art products which lack a Sc₂O₃ grain
30 boundary phase, as is explained fully hereinbelow.

[0033] Figure 2 shows an X-ray diffraction pattern of a sintered silicon nitride product prepared according to one embodiment of the invention. The X-ray diffraction pattern shows the predominance of β -silicon nitride, together with distinct peaks attributable to scandium oxide, scandium disilicate, and silicon carbide.

[0034] A number of sintered silicon nitride products of the invention were prepared, according to the starting mixtures listed in Table 1, as described in the below Examples. The properties of such sintered silicon nitride products are presented in Table 3.

10

Table 1. Composition of Starting Powder Mixtures for Preparation of Various Silicon Nitride Sintered Products

Component added to mix	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample*
Si ₃ N ₄	90.4	91.4	90.4	87	86	88	83	83
Sc ₂ O ₃	6	8	7.7	8	7.7	7.7	12	6
SiO ₂	3	0	1.3	0	1.3	1.3	0	6
SiC	0.6	0.6	0.6	5	5	3	5	5
Mass Total	100	100	100	100	100	100	100	100
SiO ₂ /Sc ₂ O ₃ molar ratio ¹	1.95	0.59	0.99	0.56	0.97	0.97	0.36	2.98

* outside the scope of this invention;

15 ¹ includes 1.2 wt. % oxygen conversion to SiO₂ in the Si₃N₄ starting component.

EXAMPLES

Example 1

[0035] Samples of sintered silicon nitride products of the invention were prepared from starting materials, having the compositions of samples 1 to 7 shown in Table 1, by mixing powders of the various components to provide a starting powder mix; forming a green body from the starting powder mix; and then sintering the green bodies to >99% of their theoretical density at final temperatures of >1900°C. Sample 8 in Table 1 has composition that is outside the scope of this invention. The ceramic powders were mixed in either water or alcohol, and ball-milled for 4 to 24 hours. The silicon nitride powder was commercially available UBE E-10 powder (Ube America, Inc., New York, NY), which is predominantly α -Si₃N₄ having a surface area of approximately 10 m².g⁻¹, a low level of cationic impurities, an oxygen impurity level of approximately 1.2 weight %, and an average particle size of approximately 0.5 μ . The scandium oxide, silicon oxide, and silicon carbide were commercially available powders of at least 99 weight % purity and had an average grain size of 1.0 μ or less. The green bodies were prepared either by cold isostatic pressing (Example 2) or by slip casting (Example 3).

20

Example 2

Preparation of dry-pressed green bodies by cold isostatic pressing.

[0036] 1 kg of starting powder mixture was mixed with 2 liters of isopropyl alcohol and milled with 4 kg of milling media for 24 hours. The milled powder was dried and sieved through 100 mesh screens to provide a flow-able powder. Rubber molds of approximately 2.5 cm x 2.5 cm x 15 cm were filled with the flow-able powder, sealed, and subjected to an isostatic pressure of 25,000 psi. The compacted green bodies were about 2 cm x 2 cm x 10 cm.

30

Example 3

Preparation of green bodies by slip casting

- 5 **[0037]** 1 kg of starting powder mixture was mixed with 41 to 44 vol. % de-ionized water, and the pH adjusted to pH 9.5 to 10 using NH_4OH . The mixture was milled with 4 kg of silicon nitride mill media for 24 hours. The milled mixture was de-aired and screened, and 200 gram aliquots were poured into plaster molds until enough water was removed to make the aliquoted material semi-rigid. The semi-rigid body was then placed in a drying oven until the remaining water was removed from the green body.
- 10

Example 4

15 *Preparation of sintered silicon nitride products from green bodies*

- [0038]** The dried green bodies were sintered by gas pressure sintering, using a carbon furnace in a pressure vessel, under nitrogen gas to suppress the decomposition of silicon nitrides. Three alternative sintering cycles were used to manufacture the examples of this invention, each sintering cycle comprising four stages, as shown in Table 2. Taking sintering cycle 1 as an example, stage 1 employed a temperature of 1625-1700°C for four hours at a nitrogen pressure of 10-50 psi; stage 2 employed a temperature of 1925-1975°C for four hours at a nitrogen pressure of 100-200 psi; stage 3 employed a temperature of 2025°C for 1.5 hours at a nitrogen pressure of 350 psi. Thereafter, stage 4 employed a temperature of 2025°C for 1.5 hours at an initial nitrogen pressure of 350 psi, with the pressure being increased during stage 4 to a total or final pressure in the range of about 900 psi (350 psi N_2 + 550 psi argon) to 1500 psi (350 psi N_2 + 1150 psi argon) by the addition of from 550 to 1150 psi of argon. A four-stage sintering process was employed to manufacture the product of this invention to
- 20
- 25
- 30

achieve the desirable grain boundary phase compositions and microstructure for superior high fracture toughness and high temperature properties. The sintered body was crystallized at 1500°C under nitrogen to provide a sintered silicon nitride product in which the final grain boundary phases were mainly Sc_2O and $\text{Sc}_2\text{Si}_2\text{O}_7$ (see, e.g., Figure 2). For samples 2 to 6, the starting mixture of which had a $\text{SiO}_2/\text{Sc}_2\text{O}_3$ molar ratio equal to or less than 1, the predominant grain boundary phase of Sc_2O_3 accounted for more than 50% of the grain boundary phases.

10 **Table 2: Sintering Cycles for Formation of Silicon nitride Products**

Sintering Cycle	Stage 1	Stage 2	Stage 3	Stage 4
1	1625-1700°C, 4 hrs, 10-50 psi N_2	1925-1975°C, 4 hrs, 100-200 psi N_2	2025°C, 1.5 hrs, 350 psi N_2	2025°C, 1.5 hrs, 350 psi N_2 + 550-1150 psi Ar
2	1825°C, 2hrs, 100 psi N_2	1950°C, 3 hrs, 150 psi N_2	2015°C, 1 hr, 350 psi N_2	2015°C, 1 hr, 350 psi N_2 + 550-1150 psi Ar
3	1800°C, 2 hrs, 100 psi N_2	1925°C, 3 hrs, 125 psi N_2	2000°C, 1 hr, 350 psi N_2	2000°C, 1 hr, 350 psi N_2 + 550-1150 psi Ar

15 [0039] Table 3 shows the properties of sintered silicon nitride products prepared from the starting mixtures listed in Table 1. The data in Table 3 is for the average result of replicate tests for fracture toughness, oxidation weight gain, and sintered density. The oxidation weight gain data is a measure of the oxidation resistance of the various sintered silicon nitride products at

temperatures of up to 1500°C. Sintered silicon nitride products of the invention typically exhibit an oxidation weight gain at a temperature of 1500°C in the range of from about 0.27 to 0.45 mg.cm⁻², and usually from about 0.27 to 0.38 mg.cm⁻².

5 [0040] The fracture toughness reported herein (Table 3) was measured by one particular method, namely the indentation strength method at a 20 kg indentation load. It is well known in the art that other fracture toughness measurement methods and calculations tend to yield higher fracture toughness values for ceramic materials. The indentation strength method applied here is a
10 more reliable and accurate measurement method to evaluate the fracture toughness property of a given material.

[0041] The fracture toughness of 8.1 MPa.m^{0.5} for those sintered products shown in Table 3 corresponds to a 20-kg indentation fracture strength of 350 MPa for bend bars of the sintered products with 20kg Vickers
15 indentations on the tensile surface as the fracture origin. This high retained-strength of indented bars reveals strong damage resistance, hence the true high fracture toughness property of the products of this invention.

Table 3: Properties of Sintered Silicon Nitride Products

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Sample	Fracture Toughness (MPa.m ^{0.5})	Oxidation wt. Gain, 1000°C/100 h (mg.cm ⁻²)	Oxidation wt. gain, 1400°C/100 h (mg.cm ⁻²)	Oxidation wt. gain, 1500°C/100 h (mg.cm ⁻²)	Sintered density (g.cm ⁻³)
1	7.7	0.05	0.05	0.38	3.21
2	8.3	0.05	0.15	0.30	3.20
3	8.1	0.01	0.19	0.27	3.21
4	8.5	0.02	0.2	0.35	3.19
5	8.1	0.03	0.21	0.33	3.21
6	8.4	0.06	0.26	0.45	3.21

7	8.0	0.04	0.22	0.40	3.22
8*	2.8	0.05	0.19	0.34	3.17

*Outside the scope of this invention

[0042] The high fracture toughness and strong oxidation resistance of sintered silicon nitride products of the invention are important properties for applications in gas turbine engine hot section components. While not being bound by theory, Applicant believes that the property of high fracture toughness exhibited by sintered silicon nitride products of the invention is a result of the acicular microstructure of the sintered products developed from the four-stage sintering process (e.g., Table 2), and from the existence of crystalline grain boundary phases, e.g., of Sc_2O_3 , that have a coefficient of thermal expansion (CTE) much higher (e.g., up to $>2x$) than that of the β -silicon nitride grain. As a comparison, the $\text{Si}_2\text{N}_2\text{O}$ grain boundary phase (as in prior art products) has a CTE of $\sim 3 \times 10^{-6} \text{ }^\circ\text{K}^{-1}$, which is almost the same as that of the β -silicon nitride grain. In contrast, the Sc_2O_3 grain boundary phase in products of the present invention has a CTE of $8 \times 10^{-6} \text{ }^\circ\text{K}^{-1}$, which is more than two times ($2x$) higher than the CTE of silicon nitride. The high residual stresses resulting from the mismatch in thermal expansion between the Sc_2O_3 grain boundary phase and the silicon nitride grains, in products of the invention, enhances the debonding of the β -silicon nitride grains, and increases the fracture toughness to $> 8 \text{ MPa.m}^{0.5}$.

[0043] Furthermore, products of this invention show strong oxidation resistance at high temperatures. For example, after 100 hour of oxidation at a temperature of 1400 or 1500°C, the weight gain is $<0.25 \text{ mg.cm}^{-2}$ and $<0.5 \text{ mg.cm}^{-2}$, respectively (see, e.g., Table 3). Additionally, the surface of the oxidized materials shows very little damage subsequent to the oxidation testing regime.

[0044] In addition, Sc_2O_3 as the grain boundary phase in the product of this

invention has no silica activity, as opposed to the grain boundary phases such as $\text{Si}_2\text{N}_2\text{O}$ or $\text{Sc}_2\text{Si}_2\text{O}_7$ of prior art silicon nitride products, which have relatively high silica activities. The lack of silica activity exhibited by Sc_2O_3 improves the high temperature environmental resistance of sintered silicon nitride products of the invention, especially in an environment, such as a gas turbine engine, having a high water vapor pressure concentration. It is well known that the recession of silicon nitride ceramics in high temperature/high water vapor environments is related to the conversion of silica into silicon hydroxide gas species. Therefore, the low silica activity in the grain boundary phase of sintered silicon nitride products of the present invention results in increased resistance to recession, as compared with prior art products which lack a Sc_2O_3 grain boundary phase.

[0045] It should be understood, of course, that the foregoing relates to preferred embodiments of the invention and that modifications may be made without departing from the spirit and scope of the invention as set forth in the following claims.